CORRECTING PROGRAMMES FOR MACHINING FREE-FORM SURFACES ON THE BASIS OF COORDINATE MEASUREMENT DATA

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Abstract:
The paper presents a methodology of correcting systematic influence of machining processes on free-form surfaces. Such correction is performed off-line by introducing alterations compensating this influence to machining programmes. The effect of systematic influence of machining are deterministic deviations of surfaces. CAD models of these deviations, averaged for a number of surfaces machined under repeatable conditions, represent machining pattern models which serve as the basis for performing correction. The basis for developing such models, are surface deviations determined during coordinate measurements carried out along a regular grid of points. For estimating surface models of deterministic deviations, the author's own methodology is proposed, in which the regression analysis, spatial statistics methods, an iterative procedure, and NURBS modelling are applied.

A machining pattern model with the opposite sign was used for compensating systematic influence of the milling process through modifying the nominal geometry data and correcting the machining programme. Surfaces machined after the correction according to the proposed methodology has been introduced are characterised by a considerably greater accuracy than these produced after the correction performed on the basis of raw measurement data.

Keywords: Coordinate measurement, Free-form surface, Deviation, Machining pattern model, Error correction

1. INTRODUCTION

Designing, manufacturing, and accuracy inspection of free-form surfaces are performed in the CAD environment. Measurements are most often conducted using NC CMM equipped with touch probes; in consequence, the coordinates of the measurement points of a discrete distribution on the measured surface are obtained [1-2]. At each measurement point, local deviation or the distance between this measurement point and the CAD model is determined. Surface deviations, and, as a result, coordinate measurement data, carry information on errors of the machining process.

Accuracy of machining can be improved off-line by means of correcting the machining programme. Such improvement consists in introducing corrections compensating machining errors to the programme. One of the methods to do that is introducing corrections on the basis of raw measurement data [3]. The nominal geometry of the surface under concern is then modified through adding local deviations with the opposite sign to the nominal CAD model. Raw measurement data include the systematic component characterised by great repeatability for subsequent surfaces machined under the same conditions, as well as the random component which is different for the particular machined surfaces [4]. Correction should be based on the repeatable effects in the machining process.

The present paper describes the methodology of correcting machining programmes on the basis of CAD machining pattern models or averaged models representing models of deterministic (systematic) deviations of a number of surfaces machined under repeatable conditions. For estimating surface models of deterministic deviations, the author's own methodology is proposed, in which the regression analysis, Moran's *I* statistics [5], an iterative procedure, and NURBS modelling are applied [1,6,7]. The machining pattern model (MPM), determined using this method, represents the most probable shape of deviations on subsequent machined surfaces.

An MPM with the opposite sign was used for compensating the influence of systematic errors in the milling process through modifying the nominal geometry data and correcting the machining programme. As a result of compensating the averaged influence of the systematic effects and of eliminating the random ones, surfaces machined after the correction according to the proposed methodology has been introduced are characterised by a considerably greater accuracy than these produced after correction performed on the basis of raw measurement data. Deviations observed after the former correction represented the random effects from the second stage of machining, which were impossible to correct, and the deterministic component of the deviations within the limits of its changeability in the machining process. The values of deviations observed on surfaces machined after the correction according to the author's own method had been introduced, were within the range of $\pm$ 9 μm. The proposed methodology has a universal character, and it can be applied for correcting deviations of free-form surfaces, generated as a result of both material-removal machining and additive machining.

2. MACHINING PATTERN MODEL

An actual surface is the effect of a complex machining process characterised by both deterministic and random phenomena. The resulting deterministic deviations are caused by deterministic errors of the machining process. Data obtained in coordinate measurements include information of a spatial character. While deterministic deviations are spatially correlated, spatially random deviations do not show spatial correlation [4,8].

In the applied methodology, the different spatial nature of deviations are the basis for separating the random component and the deterministic component [1,6]. The methodology consists in iterative modelling of the regression surface on the measurement data and in assessing the spatial randomness of the model residuals with the Moran's *I* test at the consecutive iteration stages. In order to determine a model describing deterministic deviations, the

NURBS method is applied. The NURBS surface of the p degree in the u direction and the q degree in the v direction is a vector function of two variables [6]. In iterative modelling, the number of control points is changed in both directions (for the subsequent surface degrees), and the model residuals are tested at each stage [1]. This methodology makes it possible to reject deviations (and other effects) of random character from measurement data, according to the developed criterion [7]. The regression model representing deterministic deviations takes on the CAD parametric form.

The Moran's I coefficient of spatial autocorrelation in a form which is appropriate for examining model residuals can be written as follows [6]:

$$I = \frac{n}{S_0} \frac{r^T C r}{r^T r} \qquad (1)$$

where:

r – vector of model residuals, $S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij}$,

C – weighting matrix of spatial relations between residuals in i and j location.

It is assumed, that the dependence between the data values at the i and j points decreases when the distance d_{ij} increases, this relation can be described in the following way [6]:

$$c_{ij} = d_{ij}^{-k} \qquad (2)$$

where:

$c_{ij} = 0$ for $i = j$,

k – constant ($k \geq 1$), in this work $k = 3$ is assumed [7].

After having determined the coefficient I, a test of significance for its value needs to be conducted. Positive and significant value of the I statistics implies the existence of positive spatial autocorrelation. Otherwise, lack of spatial correlation indicates spatial randomness of residuals [6].

The model with the smallest number of control points and the lowest surface degrees in the u and v directions, for which the model residuals met the criteria of a normal probability distribution and of spatial randomness, is adopted as an adequate one.

It can be expected that the shapes of deterministic deviations on subsequent surfaces machined under the same conditions will be repeatable to a great extent, which implies that there is similarity between spatial models estimating these deviations [6]. Estimating the model of deterministic deviations on the basis of a set of densely sampled surfaces through averaging the models built on these surfaces was suggested. The averaged model represents characteristic patterns left by the machining process on surfaces with a specified variability between the surfaces. The estimation uncertainty of the machining pattern model (MPM) is dependent on the machining process variability and on the number of measurement points [1,4].

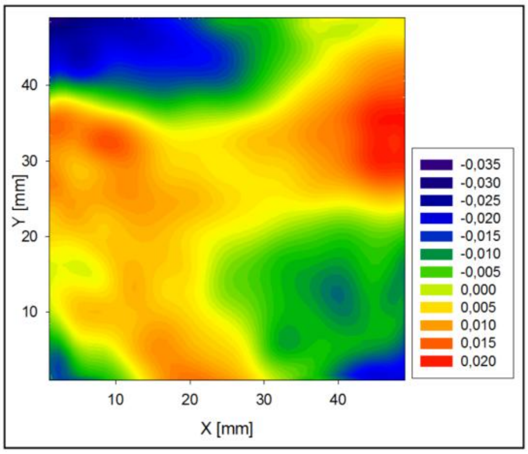
The recognition of the systematic influence, its nature, and estimating this influence in the form of a digital CAD model allow for minimising the effects of this influence on surfaces through correcting the machining programme. The nominal geometry can be modified by superimposing the reversed averaged model of systematically repeating deviations on the nominal CAD model.

3. EXPERIMENTAL RESEARCH

3.1. Machining pattern model designing

The tests were conducted on ten surfaces made of aluminium alloy with the base measuring 50 × 50 mm, milled under the same conditions using a ball-end mill of 6 mm in diameter, the rotational speed equal to 7500 rev/min, the working feed of 300 mm/min and a zig-zag cutting path in the XY plane. The measurements were carried out on a Global Performance CMM (PC DMIS software, $MPE_E = 1.5 + L/333$), equipped with a Renishaw SP25 probe and a 20 mm stylus with a ball tip of 3 mm in diameter, in which 625 uniformly distributed measurement points were scanned along a regular grid $u \times v$ (25 rows × 25 columns).

Models of deterministic deviations were created for each surface (Section 3). Regression surfaces were modelled on the obtained deviations, using an iterative procedure. The following parameters were determined for each of the residuals: the maximum value, the minimum value, the arithmetic mean, the probability distribution (normality was verified with the Kolmogorov-Smirnov test), and the coefficient of spatial autocorrelation I. The relationships between the deviations at the measurement points were made dependent on the reciprocals of the distance between the points. The elements of the weighting matrices, defining the dependencies between the deviations at points i and j, were determined from the dependence (2), assuming the value of the constant k = 3. Adequate regression models of all the surfaces under study were obtained for the number of control points equal to 15 × 15 and the surface degrees of 3 × 3. At the next stage, the models of deterministic deviations were averaged. The resulting model represented the MPM left on the machined surfaces. Mastercam X4 and Rhinoceros 3.0 software was used for surface modelling. The map of the deviations described by the MPM and the statistical characteristics of these deviations are shown in Fig. 1.



Mean	Min.	Std. dev.	Max.
−0,0004	−0,0322	0,0106	+0,0211

Fig. 1: The map versus XY plane, as well as statistical characteristics of deviations determined from MPM

3.2. Correction of machining programmes

Samples were prepared after corrections to the machining processes had been introduced. The effects of the programme correction are presented on the example of two samples. In the case of the first surface, the nominal geometry was modified by adding a reversed MPM, and in the case of the second surface – by adding the raw measurement data (Fig. 2) of one of the 10 samples (Section 3.1) with the opposite sign. The same machining and measuring parameters which had been used before the correction were applied again. The lists of the deviation values for both these surfaces can be seen in Tab. 1, and the maps of deviations are presented in Fig. 3a and 3b.

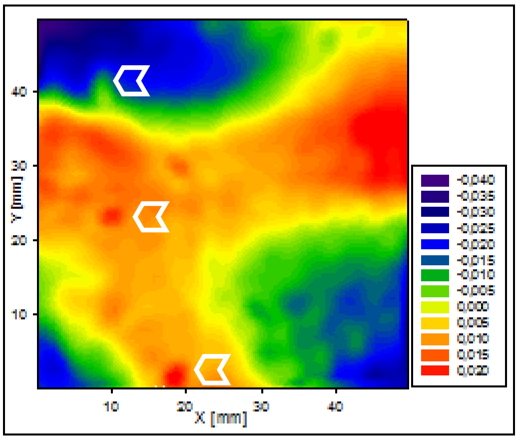


Fig. 2: Map of deviations of one of the 10 surfaces

Table 1. Results of surface measurements after correction.

[mm]	Correction on the basis of:	
	MPM	row data
Mean	0,0008	0,0003
Standard deviation	0,0027	0,0029
Min.	−0,0095	−0,0142
Max.	+0,0091	+0,0117

Analysing the obtained results (Tab. 1), a considerably better effect of performing correction on the basis of the MPM can be seen. The value of the biggest observed deviation from the nominal surface is close to the limit of the average variability range of the separated random effects (–0.0064 ÷ +0.0066). In addition, this deviation represents the deterministic component within the range of its variability (±0.0037). Observing maps of deviations (Fig. 2, Fig. 3b), it is possible to find the reason for the worse effect of correction performed on the basis of raw measurement data. The biggest deviations after the correction has been introduced are found at the locations of the greatest random deviations on the surface before the correction (with the opposite sign). The effects of random influence from the machining before the correction, which had not been removed, were transferred to the surface obtained after the correction, and they added to the random influence of the machining after the machining programme had been corrected.

After having applied the procedure described in Section 2 in separating the deterministic deviations and the random deviations on the surfaces after the correction, the results shown in Tab. 2 and in Fig. 4 were obtained. As it can be seen, the scatter of the deterministic deviation components for the two samples under concern is similar. Comparing the results concerning the random component, it can be noticed that the scatter of the random component on the sample made after the correction based on the raw measurement data is twice as big as that for the other sample. The conclusions drawn after analysing the effects of the correction performed on the basis of the raw measurement data (Fig. 2, Fig. 3b) are thus proved.

a)

b)

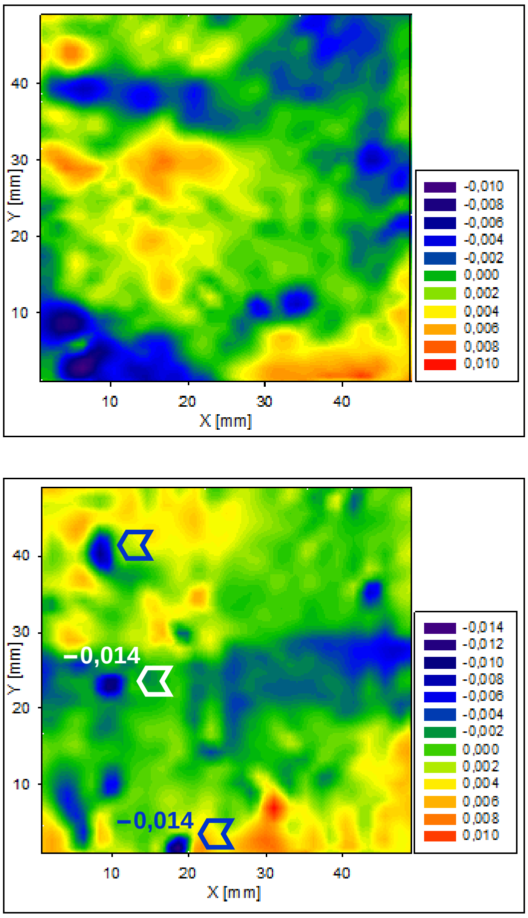


Fig. 3: Map of deviations after correction of programmes on the basis of: a) MPM, b) row measurement data

Table 2. Modelling and computations results for surfaces after correction of machining programmes.

	[mm]	Corrections on the basis of:	
		MPM	row data
Deterministic component	Mean	0,0007	0,0003
	Standard deviation	0,0025	0,0026
	Min.	−0,0072	−0,0064
	Max.	+0,0076	+0,0072
	Min. to max.	0,0148	0,0136
Random comp.	Min.	−0,0066	−0,0134
	Max.	+0,0046	+0,0090
	Mean	0,0000	0,0000
	Standard deviation	0,0011	0,0016
	Min. to max.	0,0112	0,0224

a) b) c) d)

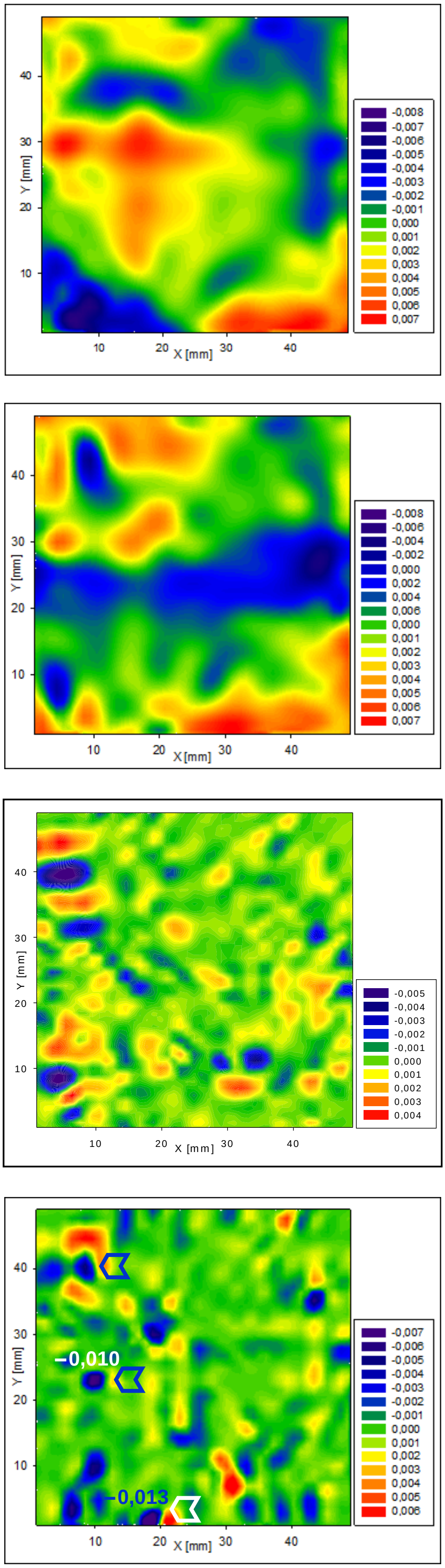


Fig. 4: Maps of deterministic and random deviations on surfaces after correction of programmes on the basis of: a) i c) – MPM, b) i d) – row measurement data

4. CONCLUSIONS

An innovative solution was applied to correcting a programme for machining free-form surfaces, consisting in using a machining pattern model (MPM). The CAD machining pattern model was obtained by averaging models of deterministic deviations of many surfaces. Removing the random component from the measurement data brought about a significant effect in the form of a greater surface accuracy after the correction based on the devised MPM. Modifying the nominal geometry on the basis of the raw measurement data resulted in the accumulation of the random influence from both stages of machining (before the correction and after it had been performed).

The essence of the proposed solution is developing a model representing to the highest possible extent the systematic influence of the machining process so that surfaces produced after the correction had been introduced are characterised exclusively by random effects which are not possible to remove. The smaller the scatter of the machining process (and thus the smaller uncertainty of estimating the MPM), the better the correction effects. The efficiency of the proposed method is going to further increase after applying SPC methods.

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